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METHOD FOR CALCULATING ROCKET ENGINE STRUCTURAL LOADS

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16. ABSTRACT

A method for calculating structural loads in a rocket engine-actuator-vehicle system is developed. The engine is attached to the vehicle by a universal-type gimbal joint and by two actuators. The engine is assumed to be a rigid body. Either the actuator loads or the engine angular acceleration is assumed to be known with a calculation of the other required. A set of algebraic equations is developed from which the unknown actuator loads or angular acceleration and the forces and moments at the gimbal point can be calculated.

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SUMMARY

All external forces acting on a rocket engine, including thrust, are applied to the engine as a known resultant force. In addition to this resultant, it is assumed that either the gimbal actuator forces applied to the engine or the angular acceleration is known. The equations of rigid body dynamics and the assumption that friction forces on the gimbal bearing surfaces are proportional to the normal forces on these surfaces are used to develop a set of algebraic equations. These equations contain the forces and moments at the gimbal point and either the actuator forces or the components of angular acceleration as unknowns. A convenient method of solving for the unknowns is given. Application of the theory to practical hardware problems is discussed.

INTRODUCTION

The guidance of many space vehicle and military rocket systems is accomplished by gimbaling (or swiveling) the engine(s) about the point where the engine attaches to the vehicle (gimbal point). In most systems the gimbaling is accomplished by extending or contracting two hydraulic cylinders (actuators) connecting the engine to the vehicle (Fig. 1).

To accomplish a rational structural design of the gimbal joint and the engine and of stage hardware in the vicinity of the engine-stage interface, it is necessary to have a reasonably accurate method of calculating loads at the interface. This report establishes a theoretical basis for calculating these loads. The theory has been successfully used as a basis for developing digital computer programs for F-1, H-1, and J-2 engine interface loads calculations.[1,2]

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1. E. S. Azary, Manual of Digital Computer Programs for Calculating Rocket Engine Loads and Gimbal Bearing Loads (Brown Engineering Company Summary Report ASD-ASTN-1070, January 1970).

2. The reference report and accompanying computer programs may be obtained from COSMIC, University of Georgia, Athens, Georgia 30601, Attn: Dr. James Carmon.

THEORETICAL DEVELOPMENT

Physical Description of Engine

Consider the typical engine-actuator system shown in Figure 1. The engine is considered a rigid body supported at the gimbal point (GP) and by the two ball-jointed struts, A and B, which represent the engine actuators. The struts may be either inextensional rods or hydraulic cylinders capable of applying loads to the engine that may cause angular accelerations about the X and U axes.

The gimbal point is a universal joint that permits the engine to swivel about the X and U axes, but is rigid with respect to a torque about the T axis. The gimbal point is capable of transmitting only frictional moments about the X and U axes.

The engine center of gravity (CG) is not generally located on any of the engine axes or symmetrically with respect to the axes.

The engine torque axis, T, is not necessarily along the engine geometrical centerline or thrust centerline. Coordinates along and orthogonal to the geometrical centerline are designated by V, ℄, U (engine coordinate system). Since the engine usually swivels or is canted with respect to the vehicle, neither the T axis nor the ℄ (geometrical centerline) axis is generally aligned with stage centerline. The vehicle coordinate system is designated by X, Y, Z. For the amount of generality assumed in this analysis for the engine-actuator-stage system, all of the coordinate systems mentioned above become aligned when the engine is not swiveled about the X or U axis. Relationships between the various coordinate systems are shown in Figure 2.

All external forces acting on the engine, including thrust, may be represented by the resultant force, F_r. Although most external forces are more naturally derived in either the stage or engine coordinate systems, these are transformed to the X, T, U system for analytical purposes to take advantage of the known fact that the gimbal bearing can transmit torque (except friction moments) only about the T axis.

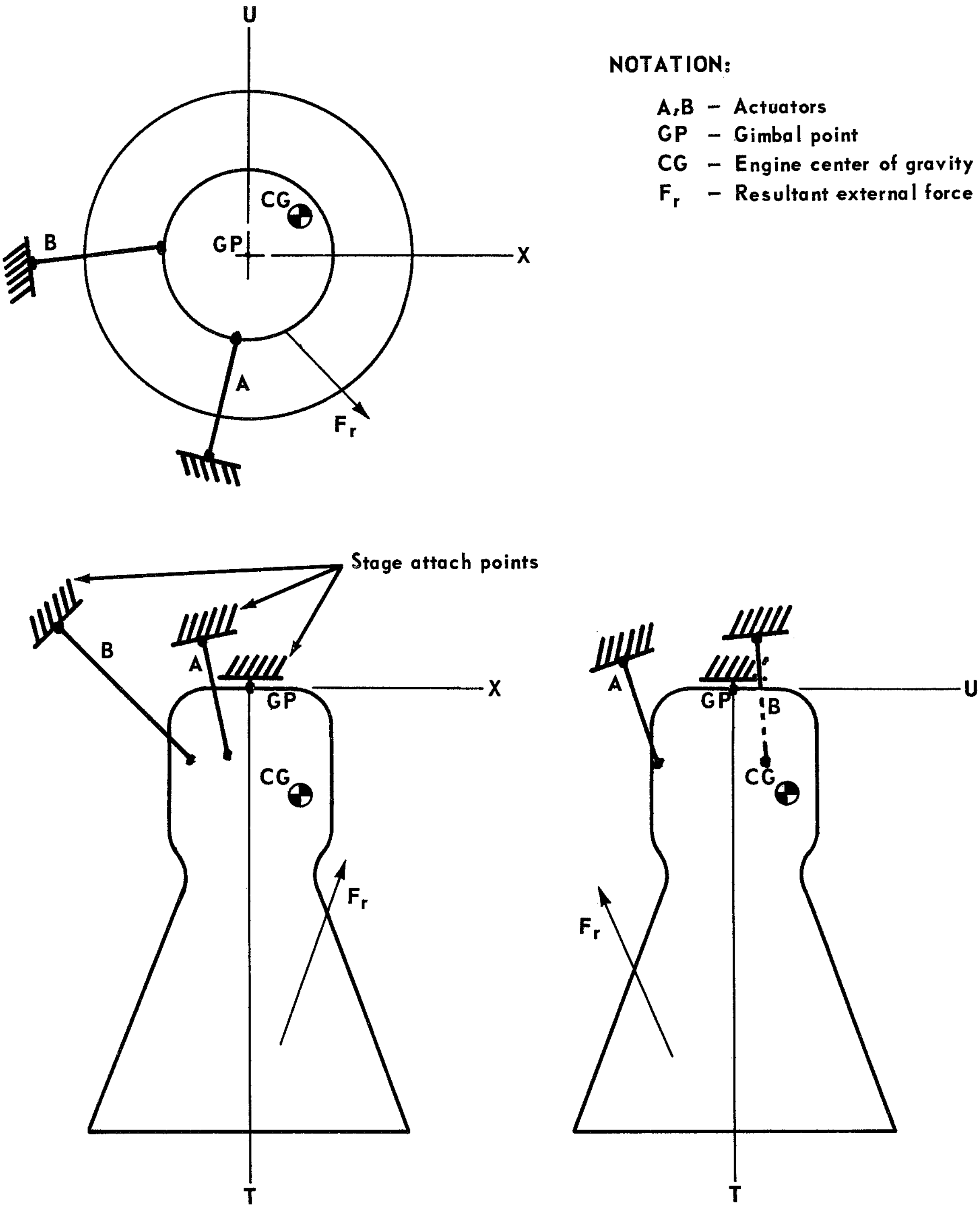
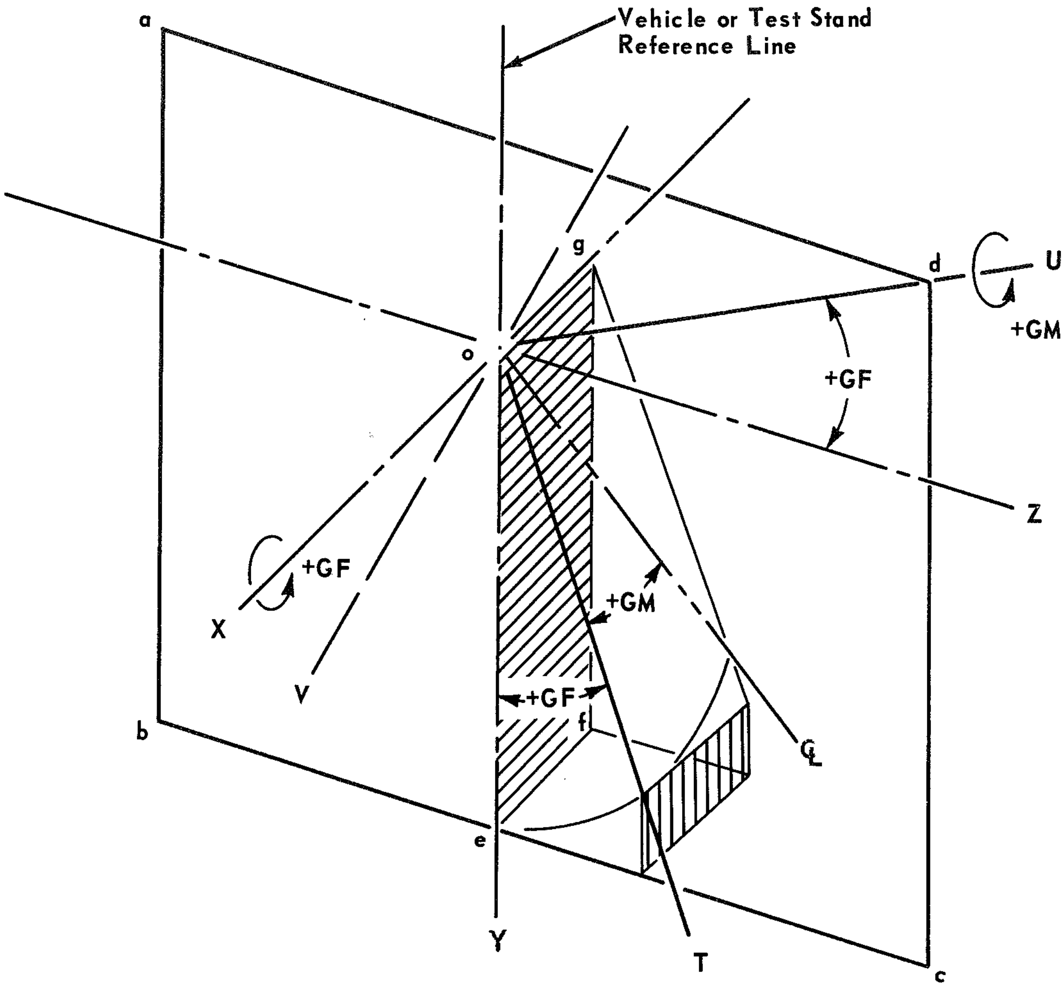


Figure 1. Engine-actuator system.



X, Y, Z – A rigid orthogonal coordinate system (vehicle system)
X, T, U – An orthogonal coordinate system (gimbal bearing system)
V, ℄ , U – An orthogonal coordinate system (engine system)
o – Gimbal center
oX – Fixed axis of gimbal bearing
oU – Moving axis of gimbal bearing
GF – Gimbal angle about oX
GM – Gimbal angle about oU
oT – Torque axis of gimbal bearing
o℄ – Centerline of gimbaled body (engine)

oT and oU are always in plane a b c d.
Plane o e f g is perpendicular to plane a b c d.
oT and oU coincide with oY and oZ when GF is zero.
All coordinate systems coincide when GF and GM are zero.

Figure 2. Relationships between coordinate systems.

Engine Freebody

Three views of the engine freebody are shown in Figure 3. The equations of rigid body dynamics are used to establish the gimbal bearing reactions in terms of the applied forces.

Let α_x be the angular acceleration of the engine about the X axis and α_u be the angular acceleration about the U axis (acceleration about the T axis is zero). These angular accelerations establish a motion of the engine CG from which the linear accelerations of the CG along the X, T, and U axes can be calculated from α_x and α_u by kinematics. The linear accelerations are denoted by a_x, a_t, and a_u respectively. Centrifugal inertial forces on the engine are usually negligible compared to other forces and are not considered in this analysis.

Six equations of equilibrium are obtained by summing forces and moments with respect to the X, T, and U axes:

$$F_{a_x} + F_{b_x} + F_{r_x} + F_x = ma_x \tag{1}$$

$$F_{a_t} + F_{b_t} + F_{r_t} + F_r = ma_t \tag{2}$$

$$F_{a_u} + F_{b_u} + F_{r_u} + F_u = ma_u \tag{3}$$

$$M_{f_a x} + M_{f_b x} + M_{f_r x} + M_x = I_x \alpha_x \tag{4}$$

$$M_{f_a t} + M_{f_b t} + M_{f_r t} + M_t = 0 \tag{5}$$

$$M_{f_a u} + M_{f_b u} + M_{f_r u} + M_u = I_u \alpha_u \tag{6}$$

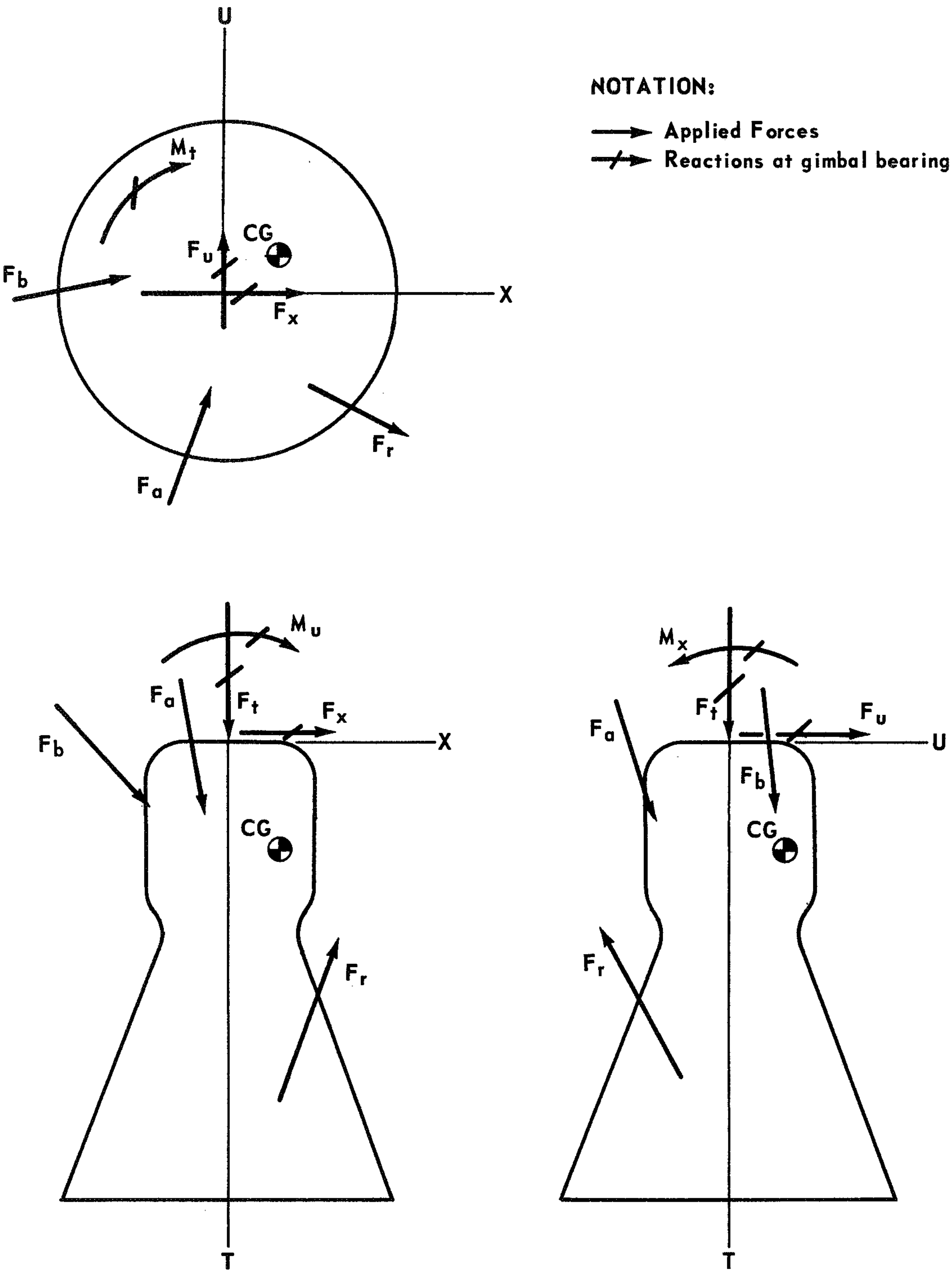


Figure 3. Engine freebody.

where F_{i_j} is the j component of force i and M_{ij} is the moment of force i about the j axis; m is the engine mass; I_x and I_u are the mass moments of inertia of the engine about the X and U axes.

In any given problem either the actuator forces, F_a and F_b, including the line of action, will be known with a solution for α_x, α_u, F_x, F_t, F_u, M_x, M_t, and M_u required or α_x and α_u will be known with a solution for F_a, F_b F_x, F_t, F_u, M_x, M_t, and M_u required. In the second instance the line of action of F_a and F_b will again be known.

The six equilibrium equations as given contain eight unknowns. However, the frictional moments, M_x and M_u, can be expressed in terms of the other forces on the gimbal point for a given gimbal bearing design. In general terms, these relationships would be,

$$\left|M_x\right| = C_1\sqrt{F_x^2 + F_t^2 + F_u^2} + C_2\left|M_t\right| \tag{7a}$$

$$\left|M_u\right| = C_3\sqrt{F_x^2 + F_t^2 + F_u^2} + C_4\left|M_t\right| \tag{8a}$$

where the C's are constants that can be determined from the gimbal bearing configuration and frictional characteristics, and $\sqrt{F_x^2 + F_t^2 + F_u^2}$ is the resultant force on the gimbal bearing. The direction or sign of M_x and M_u is such that the moment opposes the angular velocity of the engine.

For the case of zero angular velocity the C's will have different values since the static coefficient of friction rather than the dynamic coefficient will be used in determining them. The direction of M_x and M_u will be opposite the unbalanced moments about the gimbal point caused by all forces acting on the engine, including actuator forces, but excluding inertial forces. Also, the magnitudes of M_x and M_u cannot exceed the unbalanced moments about the gimbal point. That is,

$$|M_x| \leq M_{f_a x} + M_{f_b x} + M_{f_r x} \tag{7b}$$

$$|M_u| \leq M_{f_a u} + M_{f_b u} + M_{f_r u} \tag{8b}$$

for zero angular velocity. Thus, $|M_x|$ and $|M_u|$ should be calculated from both the (a) and (b) equations and the smaller value used.

A convenient method of solving the above eight equations for the unknowns by using a digital computer is as follows:

1. Assuming some initial values for unknowns M_x and M_u, calculate initial values for the other six unknowns from equations (1 through 6).

2. From these initial values of F_x, F_t, F_u, F_a, F_b, and M_t, calculate corrected values for M_x and M_u from equations (7 and 8).

3. Using corrected values for M_x and M_u, repeat steps 1 and 2. Continue to iterate through steps 1 and 2 until there is little change in the solution from one iteration to the next. The values of the unknowns obtained in this manner constitute the desired solution.

APPLICATION OF THE THEORY

Solution of the equations that have been developed yields a complete set of forces and moments on the gimbal bearing along with the corresponding forces in each actuator and the resultant angular acceleration of the engine. Forces and moments in this coordinate system are useful for analyzing certain parts in the gimbal bearing. However, for analyzing mating parts of the stage or engine the results are usually desired in the vehicle (X, Y, Z) system or engine (V, ℄, U) system. Results may be obtained in these coordinate systems by simple coordinate transformations.

A solution of the foregoing equations is valid for one very particular set of conditions on the engine. Some of the variables that affect these conditions for a given engine are engine thrust, thrust angular misalignment, thrust lateral misalignment, vehicle longitudinal, lateral, and rotational acceleration, engine gimbal angle, actuator loads, friction coefficients of gimbal bearing surfaces, engine angular acceleration, engine angular velocity, and loads from attaching hardware, such as flexible ducts. Most of the foregoing quantities vary in both magnitude and direction. Since most of the variables are independent of each other, a very large number of physically possible combinations of them exists, resulting in the same large number of possible sets of loads on the gimbal bearing.

The number of possible sets of loads is so large that a digital computer program is required to calculate each possible load case and sort out the most critical cases for output. To accomplish this, some definition of what constitutes a critical case is required. One method of reasonably assuring that the critical cases for structural design and analytical purposes are obtained is to define a critical case as one that contains a maximum or minimum value of any one of the forces or moments at the gimbal point. Thus, from the large number of possible sets of loads at the gimbal point a computer program can be devised to select and output the 12 cases that contain the maximum and minimum values of each of the six forces and moments at the gimbal point. Computer programs for the F-1, H-1, and J-2 engines of the Saturn V and Saturn IB systems have been developed by application of the theory given in this report and are documented by Azary.[3]

CONCLUSIONS

The theory developed in this report serves as a suitable basis for development of digital computer programs to calculate loads at engine-vehicle interfaces for purposes of structural design and analysis. The theory has already been successfully applied to the engines and stages of the Saturn IB and Saturn V systems.[4]

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National Aeronautics and Space Administration
Marshall Space Flight Center, Alabama 35812, March 2, 1970
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3. Op. cit.

4. Ibid.

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